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TECHNICAL REPORT
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THERMAL CONDUCTIVITY OF PYREX GLASS: SELECTED VALUES

by

LOIS C. K. CARWILE and HAROLD J. HOGE

Project reference: 1P014501B11A

March 1966

UNITED STATES ARMY
NATICK LABORATORIES
Natick, Massachusetts 01760

US ARMY MATERIEL COMMAND

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FOREWORD

This report is the first of a series on the thermal conductivities of materials of scientific and engineering interest. The values selected are based on thorough study and critical evaluation of published investigations. In a critical survey such as this one, much depends on the judgment of the surveyors. The care that the authors of the present survey have exercised may be judged from the comments they have made on the individual papers examined. Their comments on the more important papers are in the text of the report. In addition, they have made many brief comments on less important papers; these comments are given as annotations, immediately following the listing of the paper in the references.

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ABSTRACT

The published literature on the thermal conductivity of Pyrex glass has been assembled and the results critically evaluated. Best values of thermal conductivity as a function of temperature have been selected. These are presented in both graphical and tabular form; they cover the range 50 to 850° K. An attempt was made to consult all work that could significantly affect the choice of best values. Published papers were located with the aid of _Chemical Abstracts_, _Physics Abstracts_, the _Thermophysical Properties Retrieval Guide_, and some other general sources. In addition, relevant references in the papers themselves were followed up until a substantially "closed system" had been generated, as shown by the fact that no new references were being turned up.

Introduction

Pyrex glass has sometimes been used as a standard material for the calibration or checking of thermal-conductivity apparatuses, and a knowledge of its conductivity is often required for the making of corrections. Pyrex is a trade-mark name of the Corning Glass Works, and is not necessarily limited to glass of a single composition. However, there is strong indication that "Pyrex chemical resistant glass, Code No. 774" is the glass that has been used by many investigators. In recent years "Code No. 7740" has been adopted as the preferred designation for the same glass.

The British glass sold under the trade-mark name "Phoenix" is stated by the manufacturer (24) to be near in composition to Pyrex. Thermal conductivities of Phoenix glass have been included in the survey and in the graphs, because of the lack of data on Pyrex at low temperatures. All data referring to Phoenix glass are so identified.

Morey (25) gives for the composition of Code No. 774, in weight percent: SiO_2, 80.5; B_2O_3, 12.9; Na_2O, 3.8; K_2O, 0.4; Al_2O_3, 2.2. Other investigators give compositions that do not differ greatly from this composition. For example, the B_2O_3 content quoted by 5 different investigators ranged from 11.50 to 12.9. Small differences in composition are not expected to affect the thermal conductivity appreciably, except possibly when an impurity is present that affects the transmission of radiant energy.

For the density of Pyrex, the value found by Stephens (4) is probably as reliable as any. He found by direct measurement, $\rho = 2.233$ g cm^{-3} at 21° C. Five other values from the references quoted in this report range from 2.22 to 2.234.

Selection of the Values

The data were evaluated by graphical methods. Deviation plots were used, in which an equation represents the data approximately and departures from the equation are plotted; it was ultimately decided that the scattering of the data was so great that deviation plots were unnecessary, and simple graphs of thermal conductivity versus temperature were used. The original data of some investigators were given only in graphical form. In such cases the abscissa and ordinate of

each plotted point were read from the graph and recorded for subsequent use.

The selected relation between thermal conductivity and temperature is shown by the master curve in Fig. 1. Table 1.1 represents this master curve; it was obtained by reading values at uniform intervals from a large-scale version of the figure. The values were differenced and when necessary smoothed, but the table and the curve were kept consistent. The data from references (1) to (10) are shown in Fig. 1. These are considered the more important papers. References (11) to (19) contain data not plotted in the figure; often they contained only a single k-value. In one case the data had not been released for publication.

The greatest weight has been given to the data in the first three references listed. Birch and Clark (1) made absolute measurements with a guarded hot-plate. Lucks, et al. (2) made measurements relative to an Armco-iron standard, with the same heat flow in both the standard and the Pyrex. Challoner, Gundry, and Powell (3) made absolute measurements with radial heat flow in a sample in the form of a tube.

The data of Stephens (4) appear to be low, but their precision is high and they bridge the gap between about 90°K and room temperature. The value of k at 25°C accepted by Stephens appears to contain a transposition. We have corrected this by using the value 0.00253 instead of the published value 0.00235. This makes the data of Stephens self-consistent. A further increase in this reference value would raise all of Stephens' values proportionally. Plummer, Campbell, and Comstock (6) measured thermal diffusivities, and used accepted values of specific heat and density to calculate thermal conductivity. Their values are the lowest reported in the major investigations.

The only values below 90°K are those of Berman (7) and of Wilkinson and Wilks (8). In both investigations the glass was Phoenix rather than Pyrex. The data of Knapp (9), and of Smoke, Wisely, Ruh, Illyn, and Eichbaum (10) are high. Knapp (26) states that later work has indicated that his results are in error.

Table 1.2 is identical with Table 1.1 and with the master curve in Fig. 1 except for the change in units. Linear interpolation in a table will introduce no appreciable error when the second differences

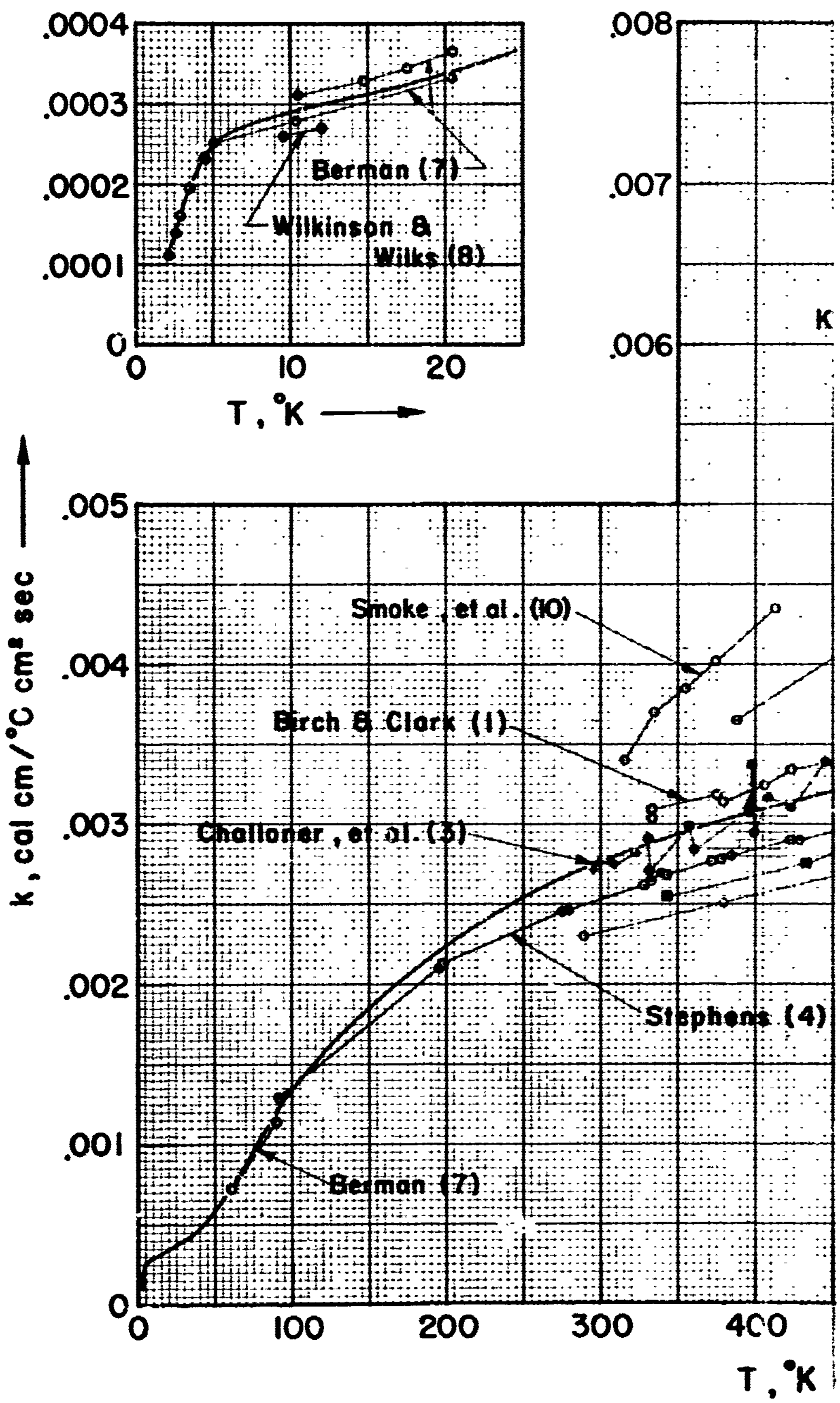

Fig. 1. Experimental data on therı
of data, (7) and (8), refe
similar to Pyrex. The smc
selected values. Low-temp
the large-scale inset grap

do not exceed 4. When second differences exceed 4, higher-order interpolation may be desirable to preserve the internal consistency of values taken from the tables. The error introduced by linear interpolation in Tables 1.1 and 1.2 will always be small compared to the uncertainty already present in the values themselves. When values outside the range of the tables are desired, they should be read directly from the master curves.

Reliability of the Tables

The master curve and the corresponding tabulated values of k are believed to be correct within ± 7 percent near room temperature. Where the data are more scarce or the measurements are more difficult, the uncertainty is greater; it may reach 15 percent at the upper limit of the data.

There is some evidence that radiative heat transfer becomes significant in Pyrex at temperatures above about $700^{\circ}K$ ($1260^{\circ}R$). Birch and Clark concluded that radiation would be negligible below $573^{\circ}K$. An upper limit for the error in k that would be caused by radiative heat transfer may be obtained by assuming the Pyrex to be perfectly transparent and the hot and cold plates to radiate and absorb as black bodies. Then, for a sample 1 cm thick, the apparent conductivity at $300^{\circ}K$ would be 6 percent greater than the true conductivity. At $500^{\circ}K$ the difference would be 23 percent; and at $700^{\circ}K$, 53 percent. These are upper limits, and the actual errors caused by lumping radiative heat transfer with conduction are probably much less. In a very thick sample the effect of radiative transfer could of course exceed the limits given above, because the difference between the apparent and the true conductivity is proportional to the thickness of the sample.

The estimated uncertainty of ± 7 percent near room temperature could be reduced to 4 or 5 percent except for the possibility that Pyrex glass may vary from sample to sample in a way not fully understood. Lucks (13) has recently measured a different sample of Pyrex in the same apparatus that was used in reference (2). The thermal conductivities found in the recent measurements, which extended from 323° to $423^{\circ}K$, are about 6 percent lower than those plotted in Fig. 1, which are taken from reference (2). The transmittances of the two samples were measured, and found to be different in the wavelength

Table 1. Thermal conductivity of Pyrex glass

(Values below 100°K are based almost entirely on data for Phoenix glass.)

Table 1.1

T	k	Δ
°K	$\frac{\text{cal cm}}{\text{°K cm}^2\text{ sec}}$	
50	0.00059	
		75
100	.00134	
		51
150	.00185	
		39
200	.00224	
		30
250	.00254	
		22
300	.00276	
		17
350	.00293	
		15
400	.00308	
		13
450	.00321	
		12
500	.00333	
		11
550	.00344	
		12
600	.00356	
		13
650	.00369	
		15
700	.00384	
		18
750	.00402	
		21
800	.00423	
		28
850	.00451	

Table 1.2

T	k	Δ
°R	$\frac{\text{Btu in.}}{\text{°R ft}^2\text{ hr}}$	
100	1.92	
		235
200	4.27	
		151
300	5.78	
		114
400	6.92	
		83
500	7.75	
		60
600	8.35	
		50
700	8.85	
		43
800	9.28	
		39
900	9.67	
		33
1000	10.0	
		4
1100	10.4	
		4
1200	10.8	
		6
1300	11.4	
		6
1400	12.0	
		8
1500	12.8	

region of 3 microns. The difference was of the proper sign to account for the difference in k, but the observed discrepancy of 6 percent seems rather large to be accounted for by any difference in transmittance.

In contrast to the experience of Lucks is that of Bullard and Niblett (11), who sent one of their measured samples of Pyrex to Birch. They report that Birch found "no perceptible difference" between the thermal conductivity of this sample and that of his own sample of Pyrex.

Data for Conversion of Units

$$T(°R) = T(°K) \times 1.8$$

$$T(°K) = t(°C) + 273.15$$

$$T(°R) = t(°F) + 459.67$$

$$\frac{\text{watt cm}}{°\text{K cm}^2} = \frac{\text{cal cm}}{°\text{K cm}^2\text{ sec}} \times 4.1840$$

$$\frac{\text{Btu in.}}{°\text{R ft}^2\text{ hr}} = \frac{\text{cal cm}}{°\text{K cm}^2\text{ sec}} \times 2902.9$$

$$\frac{\text{Btu ft}}{°\text{R ft}^2\text{ hr}} = \frac{\text{cal cm}}{°\text{K cm}^2\text{ sec}} \times 241.91$$

References

Containing data plotted in Fig. 1.

1. Francis Birch and Harry Clark, "The thermal conductivity of rocks and its dependence upon temperature and composition, Part I," Am. J. Sci, 238, 529-58 (1940).

2. C. F. Lucks, G. F. Bing, J. Matolich, H. W. Deem, H. B. Thompson, "The experimental measurement of thermal conductivities, specific heats, and densities of metallic, transparent, and protective materials," U. S. Air Force Tech. Rept. 6145, Part II (July 1952), 32 p. (AD-95239). For description of apparatus, see ref. (27).

3. A. R. Challoner, H. A. Gundry, and R. W. Powell, "A radial heat-flow apparatus for liquid thermal conductivity determinations," Proc. Roy. Soc. (London) A245, 259-67 (1958).

4. R. W. B. Stephens, "The temperature variation of the thermal conductivity of Pyrex glass," Phil. Mag. 14, 897-914 (1932).

5. W. D. Kingery, "Thermal conductivity: XIV. Conductivity of multicomponent systems," J. Am. Ceram. Soc. 42, 617-27 (1959).

6. W. A. Plummer, D. E. Campbell, and A. A. Comstock, "Method of measurement of thermal diffusivity to 1000°C," J. Am. Ceram. Soc. 45, 310-6 (1962).

7. R. Berman, "The thermal conductivities of some dielectric solids at low temperatures," Proc. Roy. Soc. London A208, 90-108 (1951). We have used the data for "Phoenix" glass. See text.

8. K. R. Wilkinson and J. Wilks, "Some measurements of heat flow along technical materials in the region 4° to 20°K," J. Sci. Instr. and Phys. in Ind. 26, 19-20 (1949). Gives data for "Phoenix" glass.

9. W. J. Knapp, "Thermal conductivity of nonmetallic single crystals," J. Am. Ceram. Soc. 26, 48-55 (1943).

10. E. J. Smoke, H. R. Wisely, Edwin Ruh, A. V. Illyn, B. R. Eichbaum, Prog. Rept. No. IV, Signal Corps Research Program, Contract DA-36-039-sc-42577 (Sept. 1 to Dec. 1 1953), 159 p.; AD-29335.

Containing data not plotted in Fig. 1; the less important, incidental, or unpublished values.

11. E. C. Bullard and E. R. Niblett, "Terrestrial heat flow in England," Monthly Notices Roy. Astron. Soc. Geophys. Suppl. 6, 222-38 (1951). They sent a sample of Pyrex to Birch, who got a value in good agreement.

12. E. H. Ratcliffe, "Preliminary measurements to determine the effect of composition on the thermal conductivity of glass," Phys. Chem. Glasses 1, 103-4 (1960). One thermal-conductivity datum is quoted from Challoner, Gundry, and Powell (3); also, the composition of the glass designated "A" establishes it as Pyrex, or something very similar to Pyrex.

13. C. F. Lucks, private communication, 17 April 1962.

14. J. B. Hersey, "A method of measuring the thermal conductivity of rock cores," J. Appl. Phys. 12, 498-501 (1941). Gives a k-value and quotes one from the Corning Glass Works.

15. Edward F. Smiley II, "The measurement of the thermal conductivity of gases at high temperatures with a shocktube; experimental results in argon at temperatures between 1000°K and 3000°K, Catholic Univ. Ph. D. Thesis (1957), 43 p.

16. Rene Reulos, "Method for the measurement of the thermal conductivity of glasses," Rev. Optique 10, 266-72 (1931).

17. P. W. Bridgman, "The thermal conductivity and compressibility of several rocks under high pressures," Am. J. Sci. 7, 81-102 (1924). Gives k of Pyrex as a function of pressure to 12,000 kg cm^{-2}.

18. W. W. Shaver, "Recent developments in glass research," in Symposium on materials research frontiers (Am. Soc. Testing Materials Special Tech. Pub. 243, 1958), p. 43-8. The k-value for Pyrex appears to be off by a factor of 12.

19. Corning Glass Works, "Pyrex laboratory glassware," Catalog LG-2 (1960), p.4.

Containing data for which another source is preferred.

20. W. D. Kingery and F. H. Norton, "The measurement of thermal conductivity of refractory materials," U. S. Atomic Energy Comm. Rept. NYO-6446 (Nov. 1954), 6 p. Appears to contain the data on which the results in reference (5) are based, but does not cover the full temperature range.

21. C. F. Lucks, H. W. Deem, and W. D. Wood, "Thermal properties of six glasses and two graphites," Bull. Am. Ceram. Soc. 39, 313-9 (1960).

22. Edward J. Smoke and John H. Koenig, "Thermal properties of ceramics," Rutgers Univ. Eng. Res. Bull. 40 (Jan. 1958), 53 p.

23. A. J. Croft, "Materials and methods for the construction of low temperature apparatus," in Experimental Cryophysics, edited by F. E. Hoare, L. C. Jackson, and N. Kurti; Butterworths, London (1961), p. 118-37. Gives data for "Pyrex and Phoenix glass" attributed to R. Berman. All values except his value for room temperature appear to have come from reference (7).

Containing no thermal conductivity data on Pyrex.

24. The British Heat Resisting Glass Co. Ltd., Bilston, Staffordshire; private communication, 27 June 1962.

25. G. W. Morey, The Properties of Glass (Reinhold Pub. Corp., 2d ed., 1954), p. 78.

26. W. J. Knapp, private communication, 20 December 1961.

27. C. F. Lucks, H. B. Thompson, A. R. Smith, F. P. Curry, H. W. Deem, and G. F. Bing, "The experimental measurement of thermal conductivities, specific heats, and densities of metallic, transparent, and protective materials," U. S. Air Force Tech. Rept. 6145, Part I (Feb. 1951), 127 p. (ATI-117715). Describes the apparatus used in reference (2).

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13. ABSTRACT

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